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THE REACTION JET AS A MEANS OF PROPULSION AT HIGH SPEEDS

By David T. Williams

SUMMARY

In order to facilitate the appraisal of the conventional jet as a means of propulsion, a simple equation is derived by means of which the performance of a large variety of aeropropulsive devices can be estimated. For any particular device with a given drag coefficient, a maximum net propulsive efficiency exists that is a function only of the mechanical energy input per unit initial energy of the air handled by the propulsive system. The conventional jet with and without mechanical compression is briefly treated. There is described and analyzed a device that is designed to provide an efficient method of achieving flight for speeds at which the conventional propeller cannot be used because of the compressibility burble.

INTRODUCTION

The efficiency of the ordinary airplane propeller falls off at high speeds because of the compressibility of the air. The decrease is apparent even at the present time and will probably become progressively more serious as airplane speeds are increased in the future.

The conventional reaction jet has been considered by many authors as a possible alternative means of propulsion (see references 1 to 8); by "conventional reaction jet" is here meant an aeropropulsive device including a furnace in which fuel is burned with air under pressure, the products of combustion being allowed to escape rearward through a nozzle. The thrust exerted by the device is the reaction to the rearward momentum of the exhaust gases. The conventional jet is presumed to be less efficient than is the ordinary airplane propeller at low air speeds; nevertheless, it is expected to be able to exert a high thrust and at the same time to be light and compact enough to actuate an airplane in high-speed flight of short duration.

Any device that propels the ambient air rearward may be considered, in a strict sense, to be a jet, whether or not all the air handled is passed through a thermal cycle. A theory of the generalized jet so defined would include both the ordinary propeller and the conventional jet as special cases. The purpose of the following analysis is to present such a theory, by means of which the optimum efficiencies andthe performance requirements for successful flight can be determined.

ANALYSIS AND DISCUSSION

The symbols used are defined as they are introduced into the discussion. For convenience, they are also listed with their definitions as appendix A.

The general equation.- The production of power for flight might be thought of as a combination of three separate processes: first, the burning of fuel in some sort of prime mover to obtain mechanical energy; second, the transfer of the mechanical energy to the air stream that passes through the mechanism; and third, the ejection of the accelerated gases rearward in order to propel the airplane. The three processes will each have an efficiency characteristic of the energy conversion involved; the ratio between the thrust work on the airplane and the heat energy of the fuel used will be a product of the three partial efficiencies.

The first partial efficiency, characteristic of the transformation of heat energy of the fuel into mechanical energy, will be called the cycle efficiency η_t and is defined by

$$\eta_t E_f = W_1 \tag{1}$$

Here E_f is the heat energy present in the fuel burned per second in the prime mover (or prime movers) of the airplane and W_1 is the mechanical work per second made available by the prime mover for transfer to the air stream handled by the device. For example, in the case of the conventional gas engine-propeller combination, η_t would be the product of the thermal efficiency and the mechanical efficiency of the engine. For a reaction jet with a mechanical compressor and with the fuel burned in a furnace, η_t would be the ratio of the theoretical increase in kinetic energy of the air stream to the heat-energy input to the prime movers. The heat-energy input E_f is equal to the product of the chemical energy in the fuel and the combustion efficiency of the burning process.

The second partial efficiency, the general mechanical efficiency of the system η_p, is defined by

$$\eta_p W_1 = W_2 \tag{2}$$

where W_2 is the increase in kinetic energy with respect to the airplane of the expelled air handled in 1 second by the device. In particular, if the airplane speed is V_o and the velocity of the expelled air relative to the airplane is V_3, and if m is the mass of air handled per second,

$$W_2 = \frac{m}{2}\left(V_3^2 - V_o^2\right) = \eta_p W_1 \tag{3}$$

It will be convenient to find an approximate expression for η_p in terms of the geometry of the jet design. It is clear that the function of η_p is to account for the internal drag loss in the jet, that is, in the diffusor, the compressor or fan, and the nozzle. If P_L is defined as such a loss, it may be expressed in general as

$$P_L = \frac{\rho}{2} C_{D_i} V_o^3 S_i = \frac{1}{2} C_{D_i} m V_o^2 \frac{S_i}{A_o} \tag{4}$$

where ρ is the density of the air, and C_{D_i} is an over-all average drag coefficient, based on the inside duct area and varying only slowly with the velocity. The total interior surface is S_i, and A_o is the reference cross-sectional area of the air stream entering the duct at a point where the velocity is that of the free stream. In terms of P_L

$$\eta_p = \frac{W_2}{W_1} = \frac{W_1 - P_L}{W_1} \tag{5}$$

or

$$\eta_p = 1 - \frac{K}{\left(\dfrac{\eta_t E_f}{\frac{m}{2} V_o^2}\right)} \tag{6}$$

where

$$\kappa = C_{D_1} \frac{S_1}{A_0} \tag{7}$$

and is the internal drag coefficient based on the area A_0.

Now, a variable ϵ is defined by

$$\epsilon = \frac{\eta_t \ E_f}{\frac{m}{2} \ V_0^{\ 2}} \tag{8}$$

The specific energy input ϵ is the mechanical energy input per unit of initial kinetic energy of the incident air stream.

When ϵ is introduced into equation (6),

$$\eta_p = 1 - \frac{\kappa}{\epsilon} \tag{9}$$

The third partial efficiency, the wake efficiency, η_w is defined by

$$\eta_w \ W_2 = P_T \tag{10}$$

Here the thrust power, $P_T = m \ (V_2 - V_0) \ V_0$, is the product of the jet thrust and the airplane speed. From equation (10) and with the aid of equation (3)

$$\eta_w = \frac{m \ (V_2 - V_0) \ V_0}{\frac{m}{2} \left(V_3^{\ 2} - V_0^{\ 2}\right)} = \frac{2}{1 + \frac{V_3}{V_0}} \tag{11}$$

This is the well-known expression for the ideal propeller efficiency. But V_3 is known from

$$\frac{m}{2} \left(V_3^{\ 2} - V_0^{\ 2}\right) = \eta_p \ \eta_t \ E_f \tag{12}$$

so that

$$\frac{V_3}{V_0} = \sqrt{1 + \frac{\eta_t \ E_f}{\frac{m}{2} \ V_0^{\ 2}} - \kappa} = \sqrt{1 + \epsilon - \kappa} \tag{13}$$

Therefore

$$\eta_w = \frac{2}{1 + \sqrt{1 + \epsilon - \kappa}} \tag{14}$$

The thrust power P_T of the device will be given by

$$P_T = E_f \eta_t \eta_p \eta_w = E_f \eta_t \left(1 - \frac{\kappa}{\epsilon}\right) \frac{2}{1 + \sqrt{1 + \epsilon - \kappa}} \tag{15}$$

A portion of the thrust power of equation (15) will overcome the exterior drag of the duct itself. Assume that the increase in the over-all drag coefficient of the airplane associated with the duct is C_{D_e}, based on the wing area in the customary manner; the corresponding increment in power P_D used in driving the airplane may be written

$$P_D = \frac{\rho}{2} C_{D_e} V_o^3 S_w = \frac{m}{2} V_o^2 C_{D_e} \frac{S_w}{A_o} \tag{16}$$

where S_w is the wing area. If an exterior drag coefficient μ based on the original jet stream cross section A_o is defined by

$$\mu = C_{D_e} \frac{S_w}{A_o} \tag{17}$$

equation (16) can be written

$$P_D = \frac{m}{2} V_o^2 \mu = \frac{\mu \eta_t E_f}{\eta_t E_f / \frac{m}{2} V_o^2} = \frac{\mu}{\epsilon} \eta_t E_f \tag{18}$$

It is assumed that μ is dependent only on the geometrical form of the jet. The net thrust power P_{net}, that is, the thrust power available for overcoming the drag of the airplane alone after deducting P_D from the total power P_T, is defined by

$$P_{net} = \eta_t E_f \left[\left(1 - \frac{\kappa}{\epsilon}\right) \frac{2}{1 + \sqrt{1 + \epsilon - \kappa}} - \frac{\mu}{\epsilon}\right] \tag{19}$$

Two over-all efficiencies are now defined. The net propulsive efficiency $\eta_{pr} \equiv P_{net}/\eta_t E_f$ is the ratio of the net thrust power to the mechanical energy available for introduction into the air stream; the net over-all efficiency $\eta = P_{net}/E_f$ is the ratio of the net thrust power to the heat energy in the fuel consumed per second. (The over-all efficiencies should be carefully differentiated from the partial efficiencies η_t, η_p, and η_w previously used.)

In the net over-all efficiency

$$\eta = \eta_t \left[\left(1 - \frac{\kappa}{\epsilon}\right) \frac{2}{1 + \sqrt{1 + \epsilon - \kappa}} - \frac{\mu}{\epsilon}\right] = \eta_t \ \eta_{pr} \qquad (20)$$

it is apparent that η varies directly with η_t and η_{pr}.

The net propulsive efficiency

$$\eta_{pr} = \left(1 - \frac{\kappa}{\epsilon}\right) \frac{2}{1 + \sqrt{1 + \epsilon - \kappa}} - \frac{\mu}{\epsilon} \qquad (21)$$

is completely determined for any design of duct by the specific power input $\epsilon = \dfrac{\eta_t \ E_f}{\frac{\rho}{2} \ V_o^2}$. If the external and the internal drag coefficients μ and κ, respectively, are fixed for any type of jet, the scale of the jet may be arbitrarily changed without altering the efficiency of the device by maintaining ϵ constant.

The general manner of variation of η_{pr} with ϵ is shown in figure 1 for various values of κ and μ. In every case η_{pr} rises rapidly with an increase in ϵ to a flat maximum and then falls slowly. The maximum efficiency $(\eta_{pr})_{max}$ is lower and the corresponding abscissa ϵ_{max} is larger, the larger κ or μ is; that is, the maximum obtainable net propulsive efficiency decreases as the duct drag, either interior or exterior, is increased while the specific power input required for the attainment of maximum η_{pr} increases with κ or μ.

Now, in flight the net thrust T is equal to the net drag or

$$T = \frac{\rho}{2} \ C_D \ V_o^2 \ S_w \qquad (22)$$

where C_D is the over-all drag coefficient of the airplane when the duct drag is neglected. If the gross weight W of the airplane is given as

$$W = \frac{\rho}{2} C_L V_o^2 S_w \tag{23}$$

where C_L is the over-all lift coefficient of the airplane, then

$$T = W \frac{C_D}{C_L} \tag{24}$$

The thrust power will be $T V_o$ and the net propulsive efficiency can be written

$$\eta_{pr} = \frac{W}{\eta_t E_f} \frac{C_D}{C_L} V_o = \left(1 - \frac{\kappa}{\epsilon}\right) \frac{2}{1 + \sqrt{1 + \epsilon - \kappa}} - \frac{\mu}{\epsilon} \tag{25}$$

Equation (25) provides a means of determining the conditions under which flight will be possible for any given jet design. If μ and κ are given, a maximum value of η_{pr} can be found; then the combinations of the power loading $W/\eta_t E_f$ and the lift-drag ratio C_L/C_D required to obtain flight at any given speed can be determined. Alternatively, an indication of the maximum airplane velocity that can be attained with the given jet device may be determined when the power loading and the lift-drag ratio are known.

For any given thrust device, a value of ϵ for which η_{pr} is a maximum may be found if μ and κ are assumed independent of ϵ. If η_{pr} of equation (21) is differentiated and equated to zero, the resulting equation may be solved for ϵ_{max}, the ϵ corresponding to the maximum value of η_{pr}. The result, as derived in appendix B, is

$$\epsilon_{max} = \frac{\mu (\mu + 4)}{2} + 2\kappa + \left(\frac{\mu}{2} + 1\right) \sqrt{\mu^2 + 4 (\mu + \kappa)} \tag{26}$$

This value may be computed and inserted in equation (21) to yield the maximum net propulsive efficiency $(\eta_{pr})_{max}$ predicted for given values of μ and κ.

Figure 2 shows the variation of the maximum net propulsive efficiency $(\eta_{pr})_{max}$ with the internal drag coefficient κ for various assumed external drag coefficients μ. The slight slope of the dotted lines shows that combinations of values of μ and κ which give the same value of ϵ_{max} give the same value of $(\eta_{pr})_{max}$ within approximately 5 percent for the ranges of μ and κ considered.

<u>The conventional jet</u>.- As an illustration of the use of the theory in the prediction of performance, the case is considered of a jet without mechanical precompression, burning a mixture of gasoline and air. In this case, n and V_o are constant and the mixture strength is varied; that is, $\epsilon = \dfrac{\eta_t\ E_f}{\frac{n}{2}\ V_o^2}$ is variable only in E_f.

If equation (25) is solved for W, after $\eta_t\ E_f$ is expressed in terms of ϵ and V_o, there is obtained,

$$W = \left(\frac{C_L}{C_D}\,\frac{n}{2}\ V_o\right)\epsilon\left[\left(1 - \frac{\kappa}{\epsilon}\right)\frac{2}{1 + \sqrt{1 - \kappa + \epsilon}} - \frac{\mu}{\epsilon}\right] \tag{27}$$

The gross weight W of the airplane is seen to increase with ϵ up to its greatest possible value, namely, ϵ_s, which is attained when a stoichiometric air-fuel mixture is burned in the jet.

Further insight into the most interesting features of this type of device may be gained without extended discussion. Assume that the entire velocity head of the inducted air is transformed into pressure with an efficiency of 100 percent. Then, if all losses are neglected, the theoretical air cycle efficiency may be found by the use of familiar relations.

The initial kinetic energy of a unit mass of air will be transformed by the action of a diffuser into pressure according to the relationship

$$\frac{V_o^2}{2} = \frac{a_o^2}{\gamma - 1}\left[\left(\frac{p_1}{p_o}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{28}$$

where a_o is the velocity of sound outside the duct, p indicates pressure, γ is the ratio of the specific heats for air, and the subscripts o and 1 refer to the state of the air before and after compression, respectively.

If the air is heated at a constant pressure p_1 and if it is then allowed to expand adiabatically to the original pressure p_o, the thermal efficiency of the entire cycle is

$$\eta_t = 1 - \left(\frac{p_o}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

Since, by equation (28),

$$\left(\frac{p_o}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \frac{1}{1 + \frac{(\gamma - 1)\ V_o{}^2}{2\ a_o{}^2}}$$

the cycle efficiency η_t can be expressed as

$$\eta_t = \frac{\frac{(\gamma - 1)}{2} M^2}{1 + \frac{\gamma - 1}{2} M^2} \tag{29}$$

where M is the Mach number V_o/a_o.

If γ is assumed to be 1.4 and the temperature of the outside air is assumed to be 59° F, $a_o{}^2$ is 1.246×10^6; then, if $V_o = 900$ feet per second, M^2 is $\frac{0.81 \times 10^6}{1.246 \times 10^6}$ and η_t is 0.115. If E_f is 19,000 Btu per pound of fuel and the theoretical air-fuel ratio is 15, the energy input ϵ_s is

$$\epsilon_s = \frac{\eta_t E_f}{\frac{m}{2} V^2} = \frac{0.115 \times 32.2 \times 19000 \times 778}{\frac{15}{2} \times 0.81 \times 10^6} = 9.01$$

The weight and the kinetic energy of the fuel are here neglected.

Because the value of ϵ_s is large, the effect of μ and κ may be neglected with little error. (See fig. 1.) In such case the net propulsive efficiency will be

$$\eta_{pr} = \frac{2}{1 + \sqrt{10}} = 0.48$$

and the net over-all efficiency η is 0.055, corresponding to a fuel rate of 2.44 pounds per net thrust horsepower-hour.

Such a low efficiency would certainly limit the range of an airplane propelled by the suggested device; but, if high-speed flight of short range is desired, the lightness and the compactness of the mechanism might make it useful. Furthermore, the efficiency could be increased in a number of ways. First, the fuel-air mixture might be leaned to decrease ϵ. According to figure 1 the efficiency would increase if the mixture were leaned;; but from equation (28) it is clear that the gross weight would have to be reduced, and the size and therefore the drag of the jet would be greater at an equal value of the thrust. Second, a fan might be used to compress the air further; the over-all efficiency would be increased but the weight of the machinery used might possibly cause a reduction in the useful load even though the gross airplane weight would be increased.

In order to show the manner in which the addition of a fan for compression would affect the thermal efficiency and the weight of the mechanism, the curves of figures 3(a) and 3(b) have been plotted. The curves show the variation of efficiencies η, η_t, and η_{pr} with the ratio of the compressor power to the thrust power at air speeds of 700 and 900 feet per second, respectively.

The indicated cycle efficiency η_t of figure 3 is the mean of the efficiencies of the jet and the compressor. Let η_t' and η_t'' be the cycle efficiencies and E_f' and E_f'', the energies present in the fuel burned in the jet and the compressor engine, respectively. Then the following equation will define η_t:

$$\eta_t = \frac{\eta_t' E_f' + \eta_t'' E_f''}{E_f' + E_f''}$$

When the data were computed for the curves, this expression was used, η_t'' being assumed constant and equal to 54 percent, corresponding to the air cycle efficiency of an Otto cycle engine with a compression ratio of 7. The usual expression for the efficiency η_t' of a constant pressure air cycle is

$$\eta_t' = 1 - \left(\frac{p_o}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = 1 - \left(\frac{p_o}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}}$$

Here the value of γ is 1.4, p is the pressure, and the subscripts o, 1, and 2 refer to free-stream, compressor-intake, and compressor-outlet pressures, respectively. If the air-stream kinetic energy is assumed to be transformed into pressure with 100-percent efficiency,

$$\left(\frac{p_1}{p_o}\right)^{\frac{\gamma-1}{\gamma}} = 1 + \frac{\gamma - 1}{2} \frac{V^2}{a_o^2} = 1 + \frac{\gamma - 1}{2} M^2$$

The compressor power P_c is defined as

$$P_c = \frac{a_1^2}{\gamma - 1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] = \frac{a_o^2}{\gamma - 1}\left(\frac{p_1}{p_o}\right)^{\frac{\gamma-1}{\gamma}}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

where a_1 is the velocity of sound at the compressor intake, and the thrust power is defined in equation (19) or by

$$P_T = \eta_t E_f \eta_{pr}$$

The value of E_f is found on the assumption that the fuel has an energy of 19,000 Btu per pound. The net propulsive efficiency included in figures 3(a) and 3(b) is found by the use of equation (21), in which κ and μ are assumed negligible as compared with ϵ. The weight and the kinetic energy of the fuel are also neglected.

Three air-fuel ratios are considered in figure 3; 15:1, 30:1, and 45:1; in all cases the ratio of the compressor power to the thrust power rises rapidly with cycle efficiency, even though all drag losses are neglected. For purposes of comparison on this figure, the air cycle thermal efficiency of 54 percent is shown corresponding to that of an ordinary gasoline engine with a compression ratio of 7; also, a propulsive efficiency typical of an ordinary propeller at lower air speeds is included. The ratio P_c/P_T for a propeller-driven airplane with a propulsive efficiency of 0.85 would be 1.173. The relatively low over-all efficiency η of the jet as compared with that of a propeller-driven airplane is traceable to the low propulsive efficiency η_{pr}. This low propulsive efficiency in turn is required because the air is passed through a thermal cycle. Even when the thermal efficiency of the jet is as high as that of an ordinary airplane engine, the total efficiency is substantially lower than that of an ordinary engine-driven propeller. If P_c/P_T is used as a rough measure of the total weight of mechanism per unit thrust power, the jet is seen to have a weight advantage over the ordinary engine-propeller combination, although the efficiency is lower.

The curves of figures 3(a) and 3(b) also demonstrate the advantage of the use of some mechanical compression as a means of increasing the efficiency of the simple jet. The thermal efficiency is doubled when the ratio of the compressor power to the thrust power increases from 0 to about 0.2.

At a low value of P_c/P_T, the region corresponding to the conventional jet, the increase in air-fuel ratio is found to improve somewhat the total efficiency for a given compressor-thrust power ratio. For example, at $P_c/P_T = 0$ the value of η approaches that of η_t, which is small. A fact not evident from the curves in figure 3 is that this increase in efficiency is accompanied by some increase in drag as well as in weight of the mechanism for a given thrust power. If the mechanism is small as compared with the entire airplane, however, the efficiency might still be profitably improved in the manner indicated.

At P_c/P_T equal to or greater than 1, the effect of leaning the mixture is more marked. The cycle efficiency will approach a constant value equal to the cycle efficiency of the compressor engine as the quantity of fuel burned directly in the duct decreases. In the limit when all the fuel is burned in the compressor engine, there is no longer any necessity for greatly compressing all the air passing through the device. If the degree of compression is reduced and the quantity of air handled is increased, the system becomes the conventional gasoline engine-driven propellor and $P_E/P_T = 1/\eta_{pr}$.

In the discussion of the reaction jet with precompression, it is apparent that: (a) The conventional jet is lighter and more compact than the engine propeller for the same thrust; (b) its efficiency may be slightly increased by leaning the fuel-air mixture or by using a higher compression ratio; and (c) its over-all efficiency will be at best much less at airplane speeds in the range considered than the efficiencies of propeller-driven airplanes at lower speeds.

<u>The mechanically actuated jet</u>.- Instead of an analysis of a series of jet designs, a device is described by means of which high propulsive efficiencies may be obtained at speeds above which the propeller begins to lose efficiency because of air compressibility.

Because the cycle efficiency has a predominating influence on the specific thrust power, the prime mover will be a gasoline engine working at the highest possible compression ratio, that is, the highest possible thermal efficiency. In order to make m variable in $\epsilon = \dfrac{\eta_t\ E_f}{\frac{m}{2}\ V_0^2}$, so that the optimum value of ϵ can be utilized, the energy of the prime mover will be transmitted to an arbitrary mass of air m by means of a fan. In order to have the optimum specific thrust power as high as possible, the drag of the mechanism, interior and exterior, will be as small as possible; the mass of air handled should then be fairly large. Thus far, the ideal device answers the description of the ordinary propeller. But, at some air speeds, the compressibility burble will begin to form on the propeller. For this and higher air speeds, the propeller will be enclosed in a duct so designed that the air speed at the propeller tips will be less than the burbling speed. The internal drag of the duct will be kept as low as possible by the efficient transformation of velocity head into pressure; the propellor (now an axial compressor) will compress the air, which will then expand through a nozzle toward the rear. The details of the installation depend on the design speed and the duct drag coefficients κ and μ.

The generalized propeller-actuated jet is diagrammed in figure 4; it consists of a diffuser, a propeller or fan, and a nozzle. Three types of installation are shown in figure 5. The installation of figure 5(a) is mounted on the fusolage, and the tractor and the pusher installations of figures 5(b) and 5(c) are mounted on the wing. In figures 5(a) and 5(c) air is scavenged from the boundary layer so that some advantage can be taken of the kinetic energy induced in the air by the drag of the airplane. Stationary fins in the duct straighten out the rotational flow and serve also as struts to hold the duct rigidly to the airplane.

The preceding theory should be applied with caution to the design under consideration. The drag coefficient κ was originally assumed to be constant with respect to the specific power input ϵ. This assumption is not valid if ϵ is increased in practice by increasing the number of stages in an axial-flow compressor because κ, in such a case, will increase with ϵ. It is reasonable to assume, however, that the efficiencies of the diffuser, the compressor (or the propeller), and the nozzle are the constants η_0, η_1, and η_2, respectively. The analysis may thereupon be carried through as in appendix C. Because of the dependence of κ upon ϵ, the propulsive efficiency η_{pr} is a different function of ϵ from that expressed in equation (21). This function may be put into the same form as equation (21) by the introduction of certain auxiliary quantities; and hence previously derived expressions may be used in the determination of η_{pr} and ϵ without the necessity of further analysis.

In particular, four auxiliary quantities are defined, namely,

$$\eta_{pr}' = \eta_{pr}/\eta_1\eta_2$$

$$\epsilon' = \epsilon \cdot \eta_1\eta_2$$

$$\mu' = \mu$$

$$\kappa' = \zeta\,(1 - \eta_0\eta_2)$$

where $\zeta = 1 - (V_1^2/V_0^2)$; these auxiliary quantities will be related by an equation of the same form as equation (21) with η_{pr}, ϵ, μ, and κ replaced by the corresponding primed quantities; thus

$$\eta_{pr}' = \left(1 - \frac{\kappa'}{\epsilon'}\right) \frac{2}{1 + \sqrt{1 + \epsilon' - \kappa'}} - \frac{\mu'}{\epsilon'} \tag{21'}$$

In order to determine η_{pr} for a given ϵ, η_0, η_1, η_2, and μ, first find $\epsilon' = \epsilon\,\eta_1\eta_2$. By equation (21') with $\kappa' = \zeta\,(1 - \eta_0\eta_2)$, $\mu' = \mu$, and ϵ' as determined, find η_{pr}'; then $\eta_{pr} = \eta_1\eta_2\eta_{pr}'$ is specified. Also ϵ'_{max} can be determined by use of an equation similar to equation (26), namely,

$$\epsilon'_{max} = \frac{\mu'(\mu'+4)}{2} + 2\kappa' + \left(\frac{\mu'}{2} + 1\right)\sqrt{\mu'^2 + 4(\mu'+\kappa')} \tag{26'}$$

Thereupon ϵ_{max} and $(\eta_{pr})_{max}$ may be found as indicated.

In table I are listed special cases in which three sets of assumptions as to partial efficiencies are made for two assumed velocities. The three sets are progressively less optimistic, but there appears to be some reason to believe that even the most optimistic set is within the range of attainment. Recent unpublished tests indicate that one may hope to design the front of the duct to perform the function of a diffuser with practically 100 percent efficiency; and, as long as the velocities within the duct are low, the surface friction can supposedly be kept within the limits indicated. The exterior drag coefficient μ might be kept low by partly submerging the duct in the fuselage.

The values of $(\eta_{pr})_{max}$ listed are properly to be compared with the propulsive efficiency of an engine and a propeller on the conventional airplane. This efficiency is about 85 percent at low air speeds. It is apparent that the predicted performance of the device described is either about equal to or about five-eighths as large as that of the conventional propeller, depending on whether the first or the third set of assumptions is made.

That the power loadings predicted in table I represent rather stringent requirements is apparent from table II. In table II are listed the power loadings and the estimated lift-drag ratios for three modern airplanes; also, for reference, this table contains characteristic maximum lift-drag ratios for an NACA 4412 airfoil. The low power loadings required for flight under the conditions assumed come primarily from the fact that, whereas lift increases with V_0^2, the drag horsepower increases with V_0^3. The ratio of weight to power therefore varies inversely with V_0 even if the efficiency is in no way affected.

In order to fly with the proposed mechanism at the contemplated velocities, one must find means of decreasing the power loading or of increasing the lift-drag ratios at present attainable in aircraft or of reducing the drag of the described jet.

In the attainment of a decrease in power loading, any method of making the power plant more efficient, of decreasing its weight, or of improving its power output would be useful. Among other modifications of the conventional gasoline engine with these aims in view, may be mentioned a conspicuously successful use of the exhaust gas to obtain thrust by means of nozzles on the exhaust stacks. According to a conservative estimate based on results recently obtained by the NACA at Langley Field, it is possible to obtain, at a velocity of 700 feet per second and 900 feet per second, respectively, a 13-percent and a 16-percent net increase in thrust power beyond the thrust power obtained without use of the momentum of the exhaust. This increase in thrust power is accomplished without any increase in exhaust back pressure.

Another use for the exhaust gas may be mentioned in this connection. If the exhaust of the engine of the device described is ejected into the high-pressure region behind the propeller, its heat may be used in a constant-pressure cycle to produce additional thrust. For a specific energy input ϵ equal to 1, by the compressor, at $V_0 = 700$ feet per second, the ideal air cycle thermal efficiency of the constant-pressure cycle is about 9 percent. If an efficiency of 35 percent is assumed for the prime mover, the brake power recovery from the exhaust would be about 17 percent of the brake power and the thrust power recovery would be about 13 percent of the original brake power.

The attainable thermal efficiency would be somewhat less than the air cycle thermal efficiency. Even if the prediction is considered quite reliable in practice, certain disadvantages are inherent in this method of scavenging the heat energy of the exhaust. The efficiency of the suggested auxiliary device depends critically on the pressure at the exhaust outlet. As the thermal efficiency of the auxiliary cycle increases, the total efficiency increase is somewhat smaller; at the same time, the maximum power output obtainable from the engine is seriously reduced by the effect of back pressure in increasing the quantity of residual gases in the cylinder. It would therefore seem safe to conclude that the method in which the jet scavenges mechanical energy directly from the Otto cycle exhaust gases is preferable to the method in which the mechanical energy is sacrificed, in large part, to recover thermal energy. Other possible methods of decreasing power loading will not be discussed here.

In consideration of other methods of accomplishing flight at high velocities with a mechanically actuated jet, it is supposedly possible to increase lift-drag ratios beyond present limits. If the ratio is increased by an increase in wing loadings, some special means of landing and take-off might be required.

The improvement of the efficiency of the diffuser, the propeller, and the nozzle is properly a field of experimental investigation.

CONCLUSIONS

1. Attainable propulsive efficiencies at high speeds below sonic velocity are certain to be lower than is common at low speeds with the conventional propeller.

2. The propeller-actuated jet is designed to provide a means of propulsion at speeds between the burbling speeds for propellers and wings. It will be relatively efficient as compared with the ordinary engine-propeller or conventional jet at the same speeds.

3. Some form of the conventional jet should be capable of developing more thrust power per pound of machinery than the device considered but only at the cost of considerably reduced efficiency.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va.

APPENDIX A

SYMBOLS

A_o	cross section of inducted air stream at the point where its velocity is equal to airplane speed, square feet
$a_{o,1}$	sonic velocity at diffuser entrance and exit, respectively, feet per second
C_D, C_L	over-all drag and lift coefficients for airplane
C_{D_i}	internal drag coefficient of jet system based on inside area
C_{D_e}	external drag coefficient of a jet, based on wing area
E_f	heat energy in fuel burned per second in jet, foot-pounds per second
E_f', E_f''	energy in fuel burned per second in jet burner and in compressor engine, respectively, foot-pounds per second
E_o	energy input per second to the diffuser of a propeller-actuated jet, foot-pounds per second
E_1	energy input per second to the compressor of a propeller-actuated jet, foot-pounds per second
P_L	loss of mechanical energy by air passing through jet in 1 second, foot-pounds per second
m	mass of air passing through jet, slugs per second
M	Mach number (V_o/a_o)
$p_{o,1,2}$	pressure, at free stream, before propeller and after propeller, respectively, pounds per square foot
P_T	thrust power developed by jet, foot-pounds per second
P_D	thrust power expended in overcoming exterior drag of jet, foot-pounds per second

P_{net} net thrust power $(P_T - P_D)$, foot-pounds per second

P_c power required for compression of air in conventional reaction jet, foot-pounds per second

S_i internal surface area of duct, square feet

S_w wing area of airplane, square feet

T net thrust exerted by jet, pounds

$V_{0,1,3}$ air-stream velocity at diffuser entrance, diffuser exit, and nozzle exit, respectively, feet per second

W gross weight of airplane, pounds

W_1 mechanical energy per second produced from fuel energy by thermal cycles of jet, foot-pounds per second

W_2 net mechanical energy per second imparted to air stream passing through jet, foot-pounds per second

γ ratio of specific heats for air

ϵ specific energy input $\left(\dfrac{\eta_t\ E_f}{\frac{m}{2}\ V_0^2}\right)$

$\epsilon' = \epsilon\ \eta_1\ \eta_2$

ϵ_s specific energy input for jet without mechanical precompression burning stoichiometric air-fuel mixture

ϵ_{max} specific energy input corresponding to maximum propulsive efficiency $(\eta_{pr})_{max}$ with given μ and κ

η_t cycle efficiency $\left(\dfrac{W_1}{E_f}\right)$

η_p propeller efficiency $\left(\dfrac{W_2}{W_1}\right)$

η_w wake efficiency $\left(\dfrac{P_T}{W_2}\right)$

η_{pr} net propulsive efficiency $\left(\frac{P_{net}}{\eta_t E_f}\right)$

$\left(\eta_{pr}\right)_{max}$ maximum propulsive efficiency for given μ and κ

η net over-all efficiency $\left(\frac{P_{net}}{E_f}\right)$

$\eta_{0,1,2}$ efficiencies of diffuser, propeller, and nozzle, respectively. See appendix C for definitions

$\eta_{pr}' = \eta_{pr}/\eta_1\eta_2$

η_t', η_t'' cycle efficiencies of jet burner and compressor engine, respectively, in conventional reaction jet

$\zeta = 1 - V_1^2/V_0^2$

κ generalized internal drag coefficient of jet mechanism

$\kappa' = \zeta\,(1 - \eta_0\eta_2)$

μ, μ' generalized external drag coefficient of jet mechanism

ρ air density, slugs per cubic foot

APPENDIX B

THE DERIVATION OF THE MAXIMUM VALUE OF SPECIFIC ENERGY INPUT

Given

$$\eta_{pr} = \left(1 - \frac{\kappa}{\epsilon}\right) \frac{2}{1 + \sqrt{1 + \epsilon - \kappa}} - \frac{\mu}{\epsilon} \qquad \text{(B-1)}$$

This expression may also be written

$$\eta_{pr} = \frac{2}{\epsilon}\left(-1 + \sqrt{1 + \epsilon - \kappa} - \frac{\mu}{2}\right) \qquad \text{(B-2)}$$

In order to find the maximum value, set $\frac{d\eta_{pr}}{d\epsilon} = 0$

$$\frac{d\eta_{pr}}{d\epsilon} = \frac{2}{\epsilon^2}\left(1 - \sqrt{1 + \epsilon - \kappa} + \frac{\mu}{2}\right) + \frac{1}{\epsilon}\,\frac{1}{\sqrt{1 + \epsilon - \kappa}} = 0 \qquad \text{(B-3)}$$

Now let $\sqrt{1 + \epsilon - \kappa} = z, \quad \epsilon = z^2 + \kappa - 1$ (B-4)

After introduction of (B-4) into (B-3) and reduction

$$z^2 - (2 + \mu)\, z + 1 - \kappa = 0 \qquad \text{(B-5)}$$

Solved for z, equation (B-5) yields

$$z = \frac{2 + \mu}{2} \pm \sqrt{\frac{(2 + \mu)^2}{4} + \kappa - 1}$$

or

$$z^2 = 1 + \epsilon - \kappa = \frac{1}{4}\ (4 + 4\mu + \mu^2)$$

$$\pm\ (2+\mu)\ \sqrt{\frac{(2+\mu)^2}{4} + \kappa - 1} + \frac{1}{4}\ (4+4\mu+\mu^2) + \kappa - 1\ . \qquad \text{(B-6)}$$

If expression (B-7) is solved for ϵ with the aid of (B-4)

$$\epsilon = \frac{\mu\ (\mu+4)}{2} + 2\kappa + \left(\frac{\mu}{2} + 1\right)\sqrt{\mu^2 + 4\ (\mu+\kappa)} \qquad \text{(B-7)}$$

APPENDIX C

DERIVATION OF EQUATION FOR NET PROPULSIVE EFFICIENCY OF MECHANICALLY ACTUATED JET

Let

$$\zeta = \left(1 - \frac{V_1^2}{V_0^2}\right) \qquad \text{(C-1)}$$

where V is the speed of the airplane, and the subscripts o and 1 refer to the free stream and the propeller, respectively. The power transformed by the diffuser from air speed to air pressure is written

$$E_o = \frac{m}{2}\ (V_o^2 - V_1^2) = \frac{mV_o^2}{2}\ \zeta \qquad \text{(C-2)}$$

If η_o is the diffuser efficiency, $(1 - \eta_o)\ E_o$ is the power lost in the process. Similarly the power loss in the propeller is $(1 - \eta_1)\ E_1$, where η_1 and E_1 are the propeller efficiency and the power input, respectively, E_1 being assumed to be in the form of pressure. If η_2 is the nozzle efficiency and if the nozzle is assumed to transform into velocity the pressure increment imposed by the diffuser and the propeller, the power loss in the nozzle will be equal to $(1 - \eta_2)\ (\eta_o E_o + \eta_1 E_1)$. The total power loss will then be

$$\frac{1}{2} mV_o^2 \; \kappa = (1-\eta_o)E_o + (1-\eta_1)E_1 + (1-\eta_2)(\eta_o E_o + \eta_1 E_1) \qquad (C\text{-}3)$$

or, with the aid of equation (C-2),

$$\kappa = \zeta \, (1 - \eta_o \eta_2) + (1 - \eta_1 \eta_2) \frac{E_1}{\frac{m}{2} V_o^2}$$

$\dfrac{E_1}{\frac{m}{2} V_o^2}$ is equal to ϵ as previously defined, so finally

$$\kappa = \zeta \, (1 - \eta_o \eta_2) + \epsilon \, (1 - \eta_1 \eta_2) \qquad (C\text{-}4)$$

If this value of κ is substituted in equation (21) η_{pr}, the propulsive efficiency of the device, becomes

$$\eta_{pr} = \left[1 - \frac{\zeta(1 - \eta_o \eta_2)}{\epsilon} - (1 - \eta_1 \eta_2) \right] \frac{2}{1 + \sqrt{1 - \zeta(1 - \eta_o \eta_2) + \epsilon \, \eta_1 \eta_2}} - \frac{\mu}{\epsilon} \qquad (C\text{-}5)$$

or

$$\eta_{pr} = \eta_1 \eta_2 \left[\left(1 - \frac{\zeta(1-\eta_o \eta_2)}{\eta_1 \eta_2 \epsilon} \right) \frac{2}{1 + \sqrt{1 - \zeta(1-\eta_o \eta_2) + \eta_1 \eta_2 \epsilon}} - \frac{\mu}{\eta_1 \eta_2 \epsilon} \right] \qquad (C\text{-}6)$$

In order to put equation (C-6) into the form of equation (21) of the text, the following quantities are defined:

$$\eta_{pr}' = \frac{\eta_{pr}}{\eta_1 \eta_2} \qquad (C\text{-}7)$$

$$\epsilon' = \eta_1 \eta_2 \epsilon \qquad (C\text{-}8)$$

$$\kappa' = \zeta(1 - \eta_o \eta_2) \qquad (C\text{-}9)$$

and

$$\mu' = \mu \qquad (C\text{-}10)$$

When these quantities are introduced into equation (C-8), this equation becomes

$$\eta_{pr}' = \left(1 - \frac{\kappa'}{\epsilon'}\right)\frac{2}{1 + \sqrt{1 + \epsilon' - \kappa'}} - \frac{\mu'}{\epsilon'} \tag{21'}$$

which is identical with equation (21).

The derivation shows that, although equation (21) of the text and figures 1 and 2 do not apply directly in this instance to the propulsive efficiency η_{pr} and to the specific power input ϵ, the equation and the figures do apply to certain auxiliary quantities η_{pr}' and ϵ' that are related to η_{pr} and ϵ by equations (C-7) and (C-8), if κ and μ are replaced by κ' and μ' defined in equations (C-9) and (C-10).

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TABLE I - PREDICTED CHARACTERISTICS OF SIX ASSUMED VERSIONS OF THE MECHANICALLY ACTUATED JET

[Velocity at propeller, 600 fps; propeller tip speed; 849 fps; $\zeta = 1 - \left(\frac{V_1}{V_0}\right)^2$;

$\kappa' = \zeta\,(1-\eta_0\eta_2)$; $\mu' = C_{D_e}\frac{S_w}{A_0}$; $\epsilon_{max} = \frac{\epsilon'_{max}}{\eta_1\,\eta_2}$; $(\eta_{pr})_{max} = (\eta_{pr}')_{max}\,\eta_1\eta_2$]

Airplane	Airplane velocity (fps)	Diffuser efficiency, η_0	Propeller efficiency, η_1	Nozzle efficiency, η_2	ζ	κ'	μ'	ϵ'_{max}	$(\eta_{pr}')_{max}$	ϵ_{max}	$(\eta_{pr})_{max}$	Maximum allowable power loading (lb/bhp)	
												C_L/C_D=8	C_L/C_D=15
1a	700	0.98	0.95	0.99	0.264	0.0079	0.01	0.305	0.877	0.328	0.816	5.13	9.62
2a	700	.98	.90	.98	.264	.0106	.02	.415	.842	.471	.744	4.66	8.75
3a	700	.95	.80	.98	.264	.0182	.04	.610	.782	.803	.594	3.73	7.00
1b	900	.98	.95	.99	.556	.0167	.02	.461	.831	.496	.775	3.89	7.30
2b	900	.98	.90	.98	.556	.0222	.04	.636	.786	.721	.694	3.39	6.36
3b	900	.95	.80	.98	.556	.0389	.08	.963	.717	1.27	.545	2.67	5.00

TABLE II. - CURRENT AVAILABLE LIFT-DRAG RATIOS

AND POWER LOADINGS

	C_L/C_D	Power loading without auxiliary exhaust jet propulsion	
		(lb/thp)	(lb/bhp)
Pursuit airplane	[a]8	7.0	6.0
Transport airplane	[a]9	14.7	12.5
Bomber	[a]7	10.0	8.5
NACA 4412 airfoil:			
Rectangular; aspect ratio, 6	[b]21		
Rectangular; aspect ratio, 9	[b]25		
Elliptical; aspect ratio, 9	[b]29		

[a]At top speed.

[b]Theoretical maximum value; approximated by use of elementary airfoil theory (reference 9).

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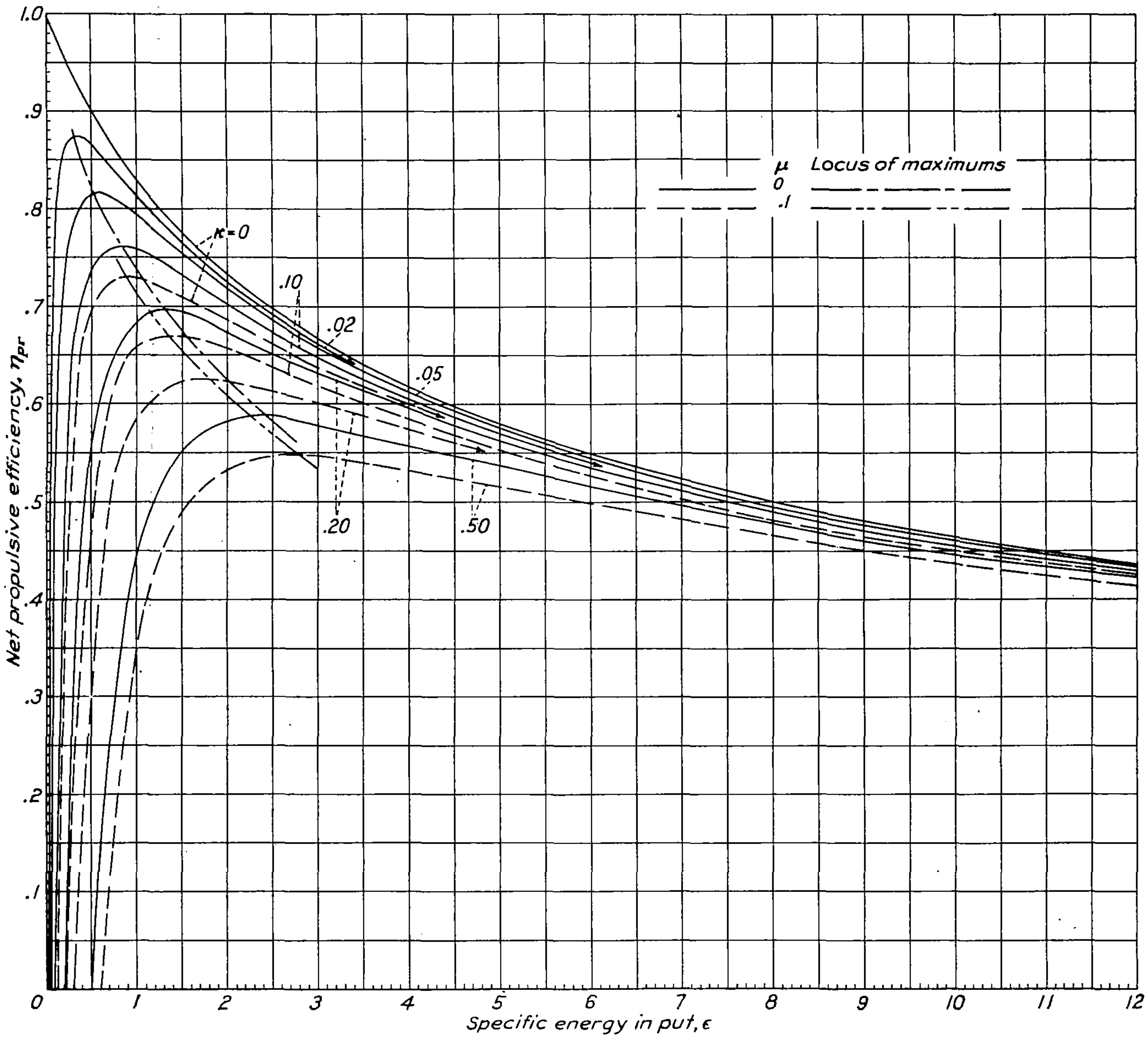


Figure 1.- The variation of net propulsive efficiency η_{pr} with specfic energy input ϵ at various external and internal drag coefficients μ and k

Fig. 1

Figure 4.- General plan of propeller-actuated jet.

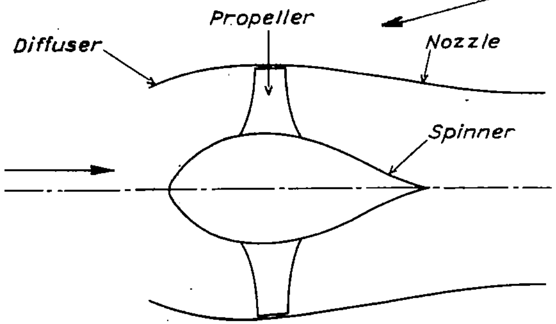
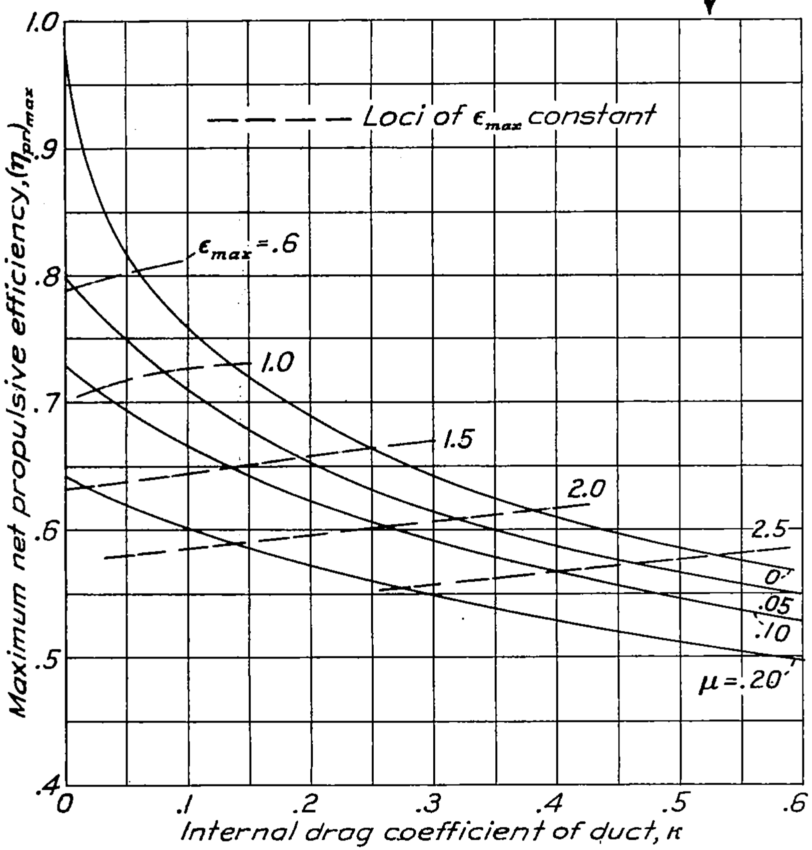
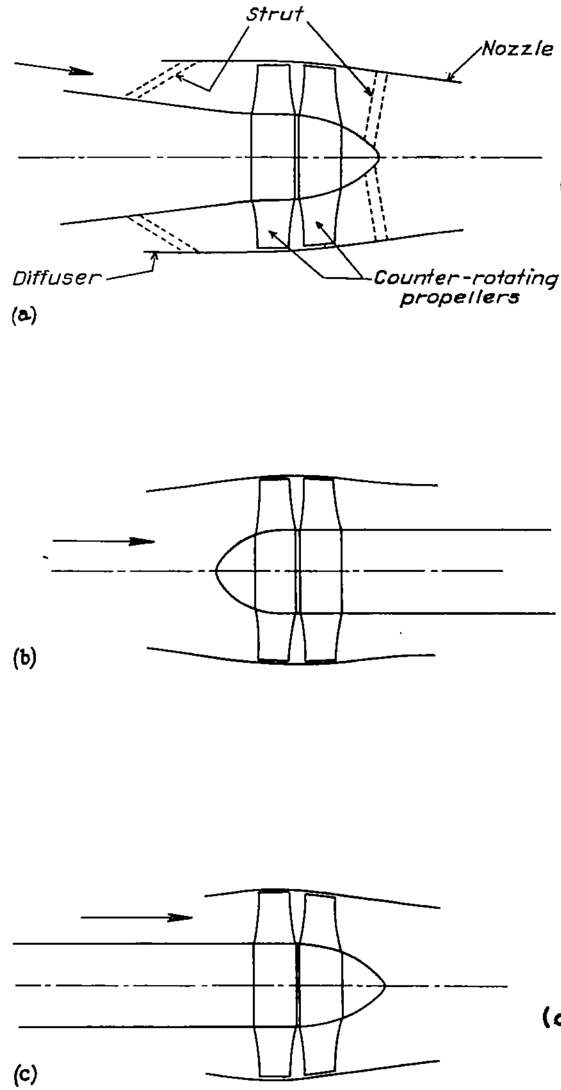


Figure 2.- Variation of maximum net propulsive efficiency $(\eta_{pr})_{max}$ with internal drag coefficient of duct κ for various external drag coefficients μ.



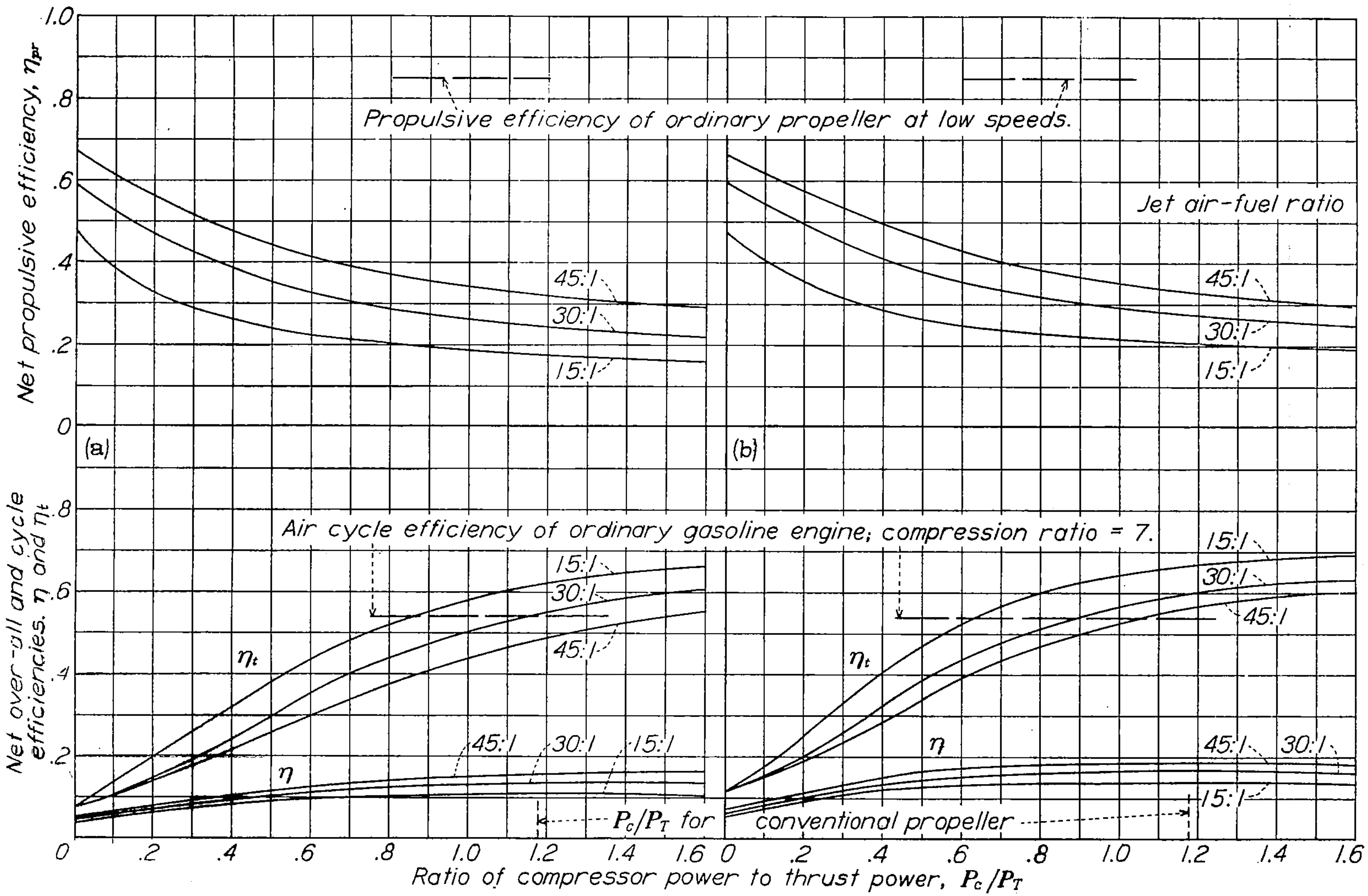


(a) Installation at rear of fuselage.

(b) Wing tractor installation.

(c) Wing pusher installation.

Figure 5.- Some applications of the propeller-actuated jet.



(a) Velocity, 700 feet per second.

(b) Velocity, 900 feet per second.

Figure 3.- Variation of efficiencies with the ratio of compressor power to thrust power for a conventional jet.

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